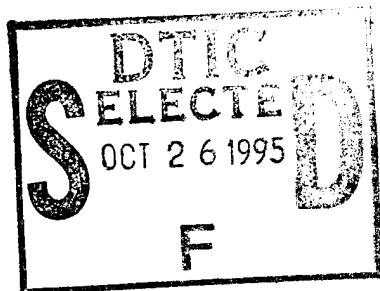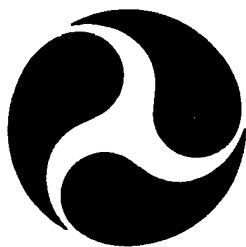Report No. CG-D-26-95

ANALYSIS OF THE IIP ICEBERG DETERIORATION MODEL

Annex G of Cost and Operational Effectiveness Analysis for
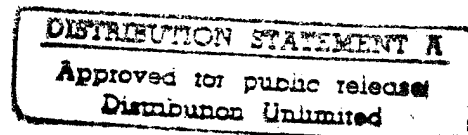*Selected International Ice Patrol Mission Alternatives*

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FINAL REPORT

JUNE 1995

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16. Abstract

This report is Interim Report Volume 7 for the Cost and Operational Effectiveness Analysis for Ice Patrol Mission Analysis Study. The International Ice Patrol has developed a model of iceberg deterioration that plays a critical role in the overall modeling of iceberg locations and determining the Limits of All Known Ice. The deterioration model, along with an iceberg drift model, is used to determine the location and state of any reported iceberg until it is resighted. The deterioration model depends on the reported size of the iceberg and a number of environmental parameters. This report examines the structure of the deterioration model, reviews empirical evaluations of the model, and conducts an analytical and experimental sensitivity analysis of the model outputs with respect to the model parameters. The result of this analysis suggests that the deterioration model is a reasonable representation of the actual deterioration process, lacking only a good mechanism for modeling the calving phenomenon. The sensitivity analysis suggests that there is little need for further accuracy in obtaining environmental parameters. The single most important factor in the application of the model is the initial estimate of iceberg size and the corresponding waterline length.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
MASS (WEIGHT)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
TEMPERATURE (EXACT)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
MASS (WEIGHT)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
TEMPERATURE (EXACT)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
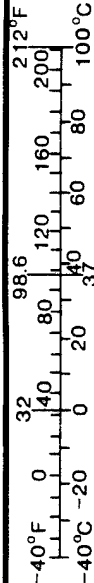
ANALYSIS OF THE IIP ICEBERG DETERIORATION MODEL

ABSTRACT

The International Ice Patrol has developed a model of iceberg deterioration that plays a critical role in the overall modeling of iceberg locations and determining the Limits of All Known Ice. The deterioration model, along with an iceberg drift model, is used to determine the location and state of any reported iceberg until it is resighted. The deterioration model depends on the reported size of the iceberg and a number of environmental parameters. This report examines the structure of the deterioration model, reviews empirical evaluations of the model, and conducts an analytical and experimental sensitivity analysis of the model outputs with respect to the model parameters. The result of this analysis suggests that the deterioration model is a reasonable representation of the actual deterioration process, lacking only a good mechanism for modeling the calving phenomenon. The sensitivity analysis suggests that there is little need for further accuracy in obtaining environmental parameters. The single most important factor in the application of the model is the initial estimate of iceberg size and the corresponding waterline length.

INTRODUCTION

Objective.

The IIP uses an Iceberg Deterioration Model to emulate the approximate deterioration behavior of icebergs in the presence of known environmental conditions. The purpose of this report is to review the structure of the existing model and to examine the sensitivity of its output with respect to changes in input parameters. This analysis identifies which input parameters require the most attention with respect to accuracy of their estimates and identifies areas where potential model enhancements are appropriate.

Background.

The iceberg deterioration model used by IIP, based on the work of White, Spaulding, and Gominho (1980), was completed and initially tested in 1983 (Anderson, 1983). The model considers four forms of deterioration: insolation (sun heating), buoyant convection (vertical circulation of the water), wind forced convection (drift movement through the water), and wave induced deterioration (wave washing of the subaerial surface). Four equations determine the melt due to each of these processes which are additive. Input data include: iceberg position; iceberg size; sea surface temperature; wave height; and wave period. Progressive deterioration of the iceberg is quantified by its

waterline "length" by definition. There are four size categories: growler, small, medium, and large with no upper limit. The model used by IIP does not include deterioration due to calving of overhanging ice slabs (Anderson, 1983). Deterioration due to calving depends on the thickness of the overhanging slab which is not generally available. Not including the deterioration due to calving underestimates the degree of deterioration in a given time period. The effect of the four forms of deterioration are illustrated in Figure 1.
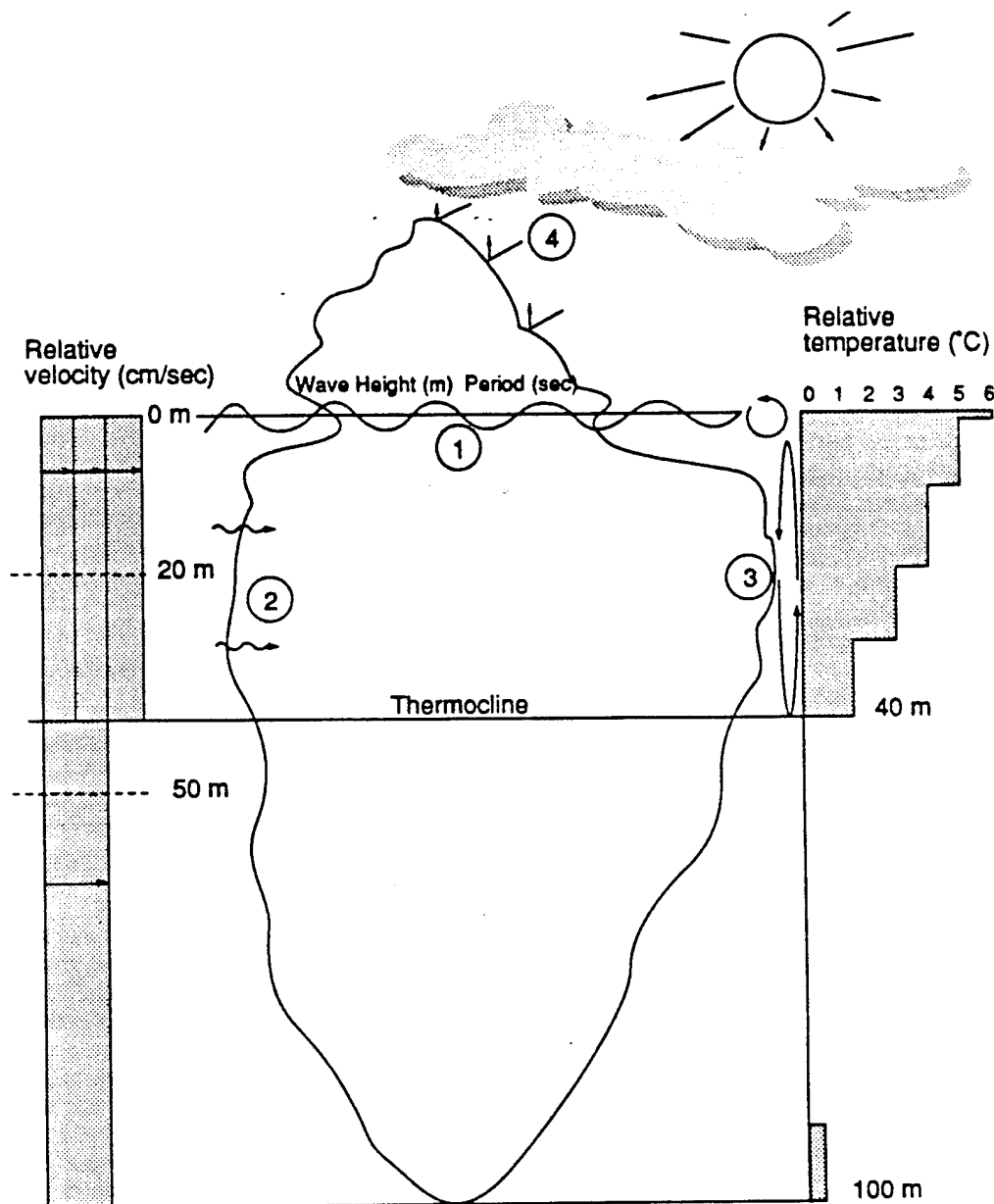
Modelled Iceberg Deterioration Processes. This figure depicts four processes used by the IIP deterioration model to "melt" icebergs. The four processes, which are labelled in order of importance are: (1) wave erosion; (2) forced heat convection; (3) buoyant heat convection; and (4) solar radiation.

Figure 1. Modeled Iceberg Deterioration Process (Hanson, 1987).

Iceberg Deterioration Model.

The Iceberg Deterioration Model (Anderson, 1983) consists of four additive components that contribute to deterioration in waterline length (cm/day) by way of heat transfer: y_1 represents deterioration due to insolation; y_2 represents deterioration due to buoyant convection; y_3 represents deterioration due to wind forced convection; and y_4 represents wave induced deterioration. Seven parameters (related to the notation of Anderson (1983)) are used to characterize these four components:

x_1 = SST (Sea Surface Temperature in °C)
x_2 = XAMP (Wave Height in cm)
x_3 = RELSPD (Relative Speed in cm/s)
x_4 = RLEN (Waterline length in m)
x_5 = IPER (Wave Period in s).
x_6 = ZTIME (in half days)
x_7 = WEATHER (1 = CLOUDY, 2 = CLEAR).

The weather in the IIP operating area is seldom clear, therefore $x_7 = 1$. To obtain melt rate per day, $x_6 = 2$. The resulting model for the total melt rate Y in cm/day is given by equation (1)

$$Y = y_1 + y_2 + y_3 + y_4 \tag{1}$$

where

Insolation:
$$y_1 = x_6 x_7/100 \tag{2}$$
$$= .02$$

Buoyant convection
$$y_2 = 0.274*(2.78T + 0.47T^2)*0.5*x_6/100$$
$$(T = x_1 \text{ - Iceberg Surface Temperature})$$
$$(\text{Iceberg Surface Temperature was held constant at } -1°C)$$
$$= 0.0012878x_1^2 + 0.0101928x_1 + 0.008905 \tag{3}$$

Wind forced convection
$$y_3 = FC (x_1 + 1)*0.5*x_6/100$$
$$= FC (x_1 + 1)/100 \tag{4}$$
$$\text{where}$$
$$FC = (0.934 - 0.202\log_{10}x_4)x_3 \qquad (x_3 < 25)$$
$$FC = (0.66 - 0.151\log_{10}x_4)(x_3 - 25) + 25(0.934 - 0.202\log_{10}x_4) \qquad (x_3 > 25)$$

and

Wave induced deterioration

• $y_4 = 0.000146 x_2 (2/x_2)^{0.2} * 24 * 3600 * [(x_1 + 1)/x_5] * 0.5 * x_6 / 100$

  $= 0.144901 x_2^{.8} (x_1 + 1) / x_5$ (5)

The model equations applied with a 6' wave height, 10 sec wave period, and 25 cm/sec relative velocity (SST unknown) result in 84 percent of the iceberg's deterioration being attributable to wave induced melting; approximately 14 percent due to wind drift of the iceberg relative to the water bathing it; and less than 2 percent related to sun heating and vertical circulation along the iceberg's submerged surface.

In the application of the model, the maximum waterline length (x_4) for the size category reported is used initially. If an iceberg is resighted, the waterline length is set to the maximum for the size reported in the resighting eliminating any deterioration which may have occurred if the resighting indicates the same or larger size. Icebergs for which no size category is reported are assumed to be medium icebergs. Note that the only melting component that depends on the size of the iceberg (waterline length) is wind forced convection melting. Thus, deterioration can be computed after the waterline length has decreased to zero. Icebergs are removed from the model when 125 percent of their original waterline length has been melted if they remain within the bounds of all known ice, unless they are limit setting icebergs for the region of all known ice in which case they are retained by the deterioration model until 150 percent of their waterline length has been melted.

QUALITATIVE AND EMPIRICAL EVALUATION OF THE MODEL

Anderson (1983) conducted an initial mathematical analysis of the model: with all other parameters held constant, a 100 meter length iceberg took 179 days to melt in -1°C water compared with 20.5 days in 3°C water. Anderson concluded that input data errors of 1°C variance from actual sea surface temperatures in this temperature range can produce melt errors on the order of 40 days for this 100 meter berg length. These results suggest that the sea surface temperature is the most critical parameter. However, other parameters were not examined and the results only hold in the range of SST considered in the analysis.

Several studies by Venkatesh, El-Tahan, and Mitten (1985), Venkatesh (1986), and El-Tahan, Venkatesh, and El-Tahan (1987) compared model performance with observed deterioration of several icebergs using observed oceanographic and meteorological data. They also developed refined size estimates. Using these data, they found good agreement between the model results and actual deterioration.

In 1987 the IIP conducted a deterioration study using 6 icebergs, observed and tracked by a surface vessel (Hanson, 1987). The time of observation on each iceberg

ranged from 2.1 days to 6.3 days. The objectives of this study were to compare iceberg deterioration predictions derived from observed environmental to predictions using system (FNMOC) data. FNMOC SST data were an average of 1.3°C colder than that actually observed, the wave heights averaged 0.9 meters higher than observed, and the periods were on average 4.6 seconds greater than observed. The 6 iceberg cluster averaged 379 cm/day melt rate of their waterline length using observed wave erosion values, while using the system operational data provided by FNMOC produced a melt rate on average of 531 cm/day. The overestimation of the predicted wave height was identified as the primary cause of the significant overestimation of the melt rate, even though the predicted temperatures also averaged 1.3°C colder, which would tend to slow the melt rate. The actual observed iceberg length changes as compared with the model predictions made as part of this test were inconclusive due to the time constraints (i.e., 2 to 6 days.)

The various studies suggest that the iceberg deterioration model is a reasonable approximation of the deterioration process when observed environmental data is used, although no iceberg has been observed to the point of 100% melt. The 1987 IIP study (Hanson, 1987) identified significant differences between the FNMOC data and observed data. In 1988, all FNMOC environmental products were improved and the new data was used by IIP (Hanson, 1988). The new values for SST, sea height, and sea period are reportedly in agreement with observed values, although no validation experiments have been reported. None of the IIP analyses or reports indicates that a complete sensitivity analysis of the deterioration model has been conducted.

SENSITIVITY ANALYSIS OF THE ICEBERG DETERIORATION MODEL

Analytic Sensitivity Analysis.

Equations (1) - (5) (with $x_6 = 2$) describe the daily melt *rate* of icebergs. Combining equations (1) - (5), the daily melt rate is

$$Y = 0.0012878x_1^2 + 0.0301928x_1 + 0.008905 + FC(x_1 + 1)/100 +$$
$$0.144901x_2^{.8}(x_1 + 1)/x_5 \tag{6}$$

and FC is defined following equation (4). The first order sensitivity of the daily melt rate to changes in parameter values can be obtained directly from equations (1) - (5) after differentiation with respect to the parameters of interest.

With respect to sea surface temperature (x_1), the change in melt rate is given by

$$\frac{\partial Y}{\partial x_1} = .0025756x_1 + .0101928 + \frac{FC}{100} + 0.144901\frac{x_2^{.8}}{x_5} \tag{7}$$

Equation (6) indicates that the melt rate is quadratic in the value of the sea surface temperature and that the rate increases with increasing temperature (equation (7)). This indicates that errors overestimating the SST have a more rapid melting effect than do corresponding underestimating errors.

With respect to wave height (x_2), the change in melt rate is given by

$$\frac{\partial Y}{\partial x_2} = 0.1159208 \frac{(x_1 + 1)}{x_2^{.2} x_5} \tag{8}$$

From equation (6), the melt rate varies as the 0.8 root of wave height. Equation (8) indicates that the change in the melt rate decreases exponentially with the wave height. This means that if the wave height is overestimated, the melt rate is also overestimated with the percent overestimation increasing at a decreasing rate.

With respect to relative speed (x_3), assuming $x_3 < 25$, the change in melt rate is given by

$$\frac{\partial Y}{\partial x_3} = \frac{(x_1 + 1)}{100} (0.934 - 0.202 \log_{10} x_4) \tag{9}$$

The melt rate varies linearly with respect to changes in relative speed. Equation (9) indicates that this rate of change is constant.

With respect to waterline length (x_4), the change in melt rate is given by

$$\frac{\partial Y}{\partial x_4} = \frac{(x_1 + 1)}{100} (-0.202 \frac{x_3}{x_4}) \tag{10}$$

The melt rate varies negatively with respect to the $\log_{10}$ of the waterline length. The rate of change of the melt rate varies negatively in inverse proportion to the waterline length. An iceberg with a longer waterline length melts slower than does one with a shorter length. Overestimating the length of an iceberg keeps it in the system longer because there is more to melt and it melts slower because it is longer.

Finally, with respect to the wave period (x_5), the change in melt rate is given by

$$\frac{\partial Y}{\partial x_5} = \frac{-0.144901 x_2^{.8} (x_1 + 1)}{x_5^2} \tag{11}$$

Equation (6) indicates that melt rate varies inversely with the wave period and equation (1) indicates that the change in the rate varies negatively in inverse proportion to the square of the wave period. A shorter wave period results in a faster melt (equation (6)).

The above analytical analysis of the model equations provides insights into the direction of the changes. In order to assess the magnitude of changes in the output (daily melt rate) with respect to changes in the input parameters, it is necessary to conduct an empirical evaluation.

Empirical Sensitivity Analysis.

Methodology.

The model was initially inspected to determine the factor or factors believed to constitute the major contribution to deterioration. An initial *nominal range sensitivity analysis* was performed to determine the factor that was dominant in the majority of different scenarios. Once this dominant factor was discovered its value alone was varied to present three different "nominal" scenarios. Within these scenarios, further univariate parametric sensitivity analysis was performed to determine how uncertainties in the other factors propagate through the model. This information was captured by perturbing their values from the "nominal" within a plausible range. The relative contributions to the uncertainty in the output are then determined.

Results.

The factors which constitute the major contribution to uncertainty are sea surface temperature x_1(SST), and wave height x_2 (XAMP). A nominal range sensitivity analysis was performed by changing their values by ten percent. It was found that x_1 was the dominant factor in the majority of scenarios. However, it should be noted that at low values of x_1, x_2 was dominant. Therefore, three different SSTs were used to dictate the three different "nominal" scenarios: 1, 6, and 15°C. The nominal values of the other factors remained constant from one scenario to another:

$$x_2 = \text{XAMP} = 6 \text{ ft } (182.9 \text{ cm})$$
$$x_3 = \text{RELSPD} = 25 \text{ cm/s}$$
$$x_4 = \text{RLEN} = 100 \text{ m}$$
$$x_5 = \text{IPER} = 10 \text{ s}$$
$$x_6 = \text{ZTIME} = 2 \text{ half-days}$$
$$x_7 = \text{WEATHER} = 1$$

Only x_2, x_3, and x_5 were perturbed uniformly by fifty percent, forty percent, and fifty percent respectively, while x_4 (waterline length) was varied by classification and with much more disparity. In all cases, misclassification obviously had the greatest effect on uncertainty in melt rate. Therefore x_2, x_3, and x_5 were considered together in terms of their relative uncertainties.

Results show that at a sea surface temperature of 1°C, changes in wave height had the greatest effect on the deterioration, followed by wave period. In fact, the uncertainty in wave height propagated roughly thirty percent more uncertainty as wave period. Relative speed had an almost negligible effect. Results at a sea surface temperature of 6°C were similar. Uncertainty in wave height propagated roughly twenty percent more uncertainty. Again, changes in relative speed had an almost negligible effect. At a sea surface temperature of 15°C, results were almost identical to those at 6°C. Detailed results are included in Appendix C in Armacost (1994).

Table 1 illustrates the impact of the joint variation in sea surface temperature and wave height on melt rate. The nominal values are indicated in boldface. Alone, a 10% variation in sea surface temperature (at 1°C) results in about a 4% variation in melt; a 10% variation in wave height alone (at 6ft) results in about 6.5% variation in melt. However, their joint 10% variation results in about 12% variation in melt.

Table 1. Ten percent parametric variation in SST (1°C) and Wave Height (6ft).

SST (°C)	XAMP(cm)	MELT(cm/day)
0.9	164.6	1.924
1.0	164.6	2.024
1.1	164.6	2.125
0.9	182.9	2.068
1.0	182.9	2.176
1.1	182.9	2.284
0.9	201.2	2.208
1.0	201.2	2.324
1.1	201.2	2.439

Table 2 includes the results when the nominal value of the sea surface temperature changes to 6°C. Now the single variation in sea surface temperature results in 8% variation in melt rate (due to the larger absolute variation in SST) while the wave height variation remains around 6.5%. The joint variation now averages 16%.

Finally, sensitivity with respect to size classification reveals the greatest opportunity for propagating uncertainty. Table 3 illustrates the time to 100% melt for three levels of sea surface temperature with other parameters held constant at their nominal values.

Table 3 makes it very clear, particularly at cold temperatures, that misclassifying an iceberg as smaller than it actually is will result in the iceberg existing long after it has been removed from the plot, even if waiting until 125% or even 150% of melt before removing the iceberg from the system.

Table 2. Ten percent parametric variation in SST (6°C) and Wave Height (6ft).

SST (°C)	XAMP(cm)	MELT(cm/day)
5.4	164.6	6.470
6	164.6	7.080
6.6	164.6	7.691
5.4	182.9	6.954
6	182.9	7.609
6.6	182.9	8.266
5.4	201.2	7.428
6	201.2	8.128
6.6	201.2	8.829

Table 3. Classification variation and time to 100% melt.

Size	SST = 1°C	SST = 6°C	SST = 15°C
Small (60 m)	26-27 days	7-8 days	3-4 days
Medium (122 m)	55-56 days	15-16 days	6-7 days
Large (225 m)	103-104 days	29-30 days	12-13 days

Summary.

The empirical analysis confirms the importance of having good estimates of sea surface temperature and wave height. The results confirm what has been known about the variation in melt with respect to changes in a single parameter. A new result from this analysis is the overall variation in melt with respect to joint variation in the parameters. The results suggest that this overall variation is superlinear (12-16% output variation for a 10% input variation). The most significant result is the impact of misclassification

Simulation analysis.

The above parametric analysis provides the opportunity to isolate sensitivity effects with respect to particular parameters. It does not however provide an ability to examine the joint effects of multiple parameters unless specific combinations of changes are examined. Clearly, this becomes computationally prohibitive and there is no effective means of evaluating the resulting outcomes. An alternative means of examining these effects is to use a simulation model that considers the parameters to be random variables with specified probability distributions. A Monte Carlo simulation then can determine the distribution of an output variable of interest. Unfortunately, such a simulation is only descriptive and simply describes the system output for a given set of inputs. It does provide the capability to examine various inputs of interest and determine how the system outputs will change.

To illustrate the capability and limitations of simulation, the deterioration model was simulated in the Excel environment to illustrate the use of simulation to evaluate the

sensitivity of policy variables. Details of the simulation are included in Appendix I. It was assumed that the input variables were independent and normally distributed with the parameters indicated in Table 4. Each simulation run involved 28 half-days. The simulation involved 100 runs (total of 2800 half days.)

Table 4. Simulation parameters.

Parameter	Mean	Standard Deviation
Wave Height	182.9 cm	30 cm
Sea surface temperature	6°C	2°C
Wave period	10 sec	1.66 sec
Relative speed	25 cm/sec	3.33 cm/sec

The purpose of the simulation is to examine the distribution of waterline lengths after 28 half days in order to evaluate berg deletion policies. The 28 half days corresponds to the approximate revisit cycle of the IIP. Assume that the iceberg drift is such that it remains in the vicinity of the LAKI (60 nm) during that period. After 100 runs for a small iceberg (60 m initial waterline length), the average waterline length is -45.17 m with a standard deviation of 7.46 m. The distribution of waterline length after 14 days is illustrated in Figure 2. The distribution is approximately normal.
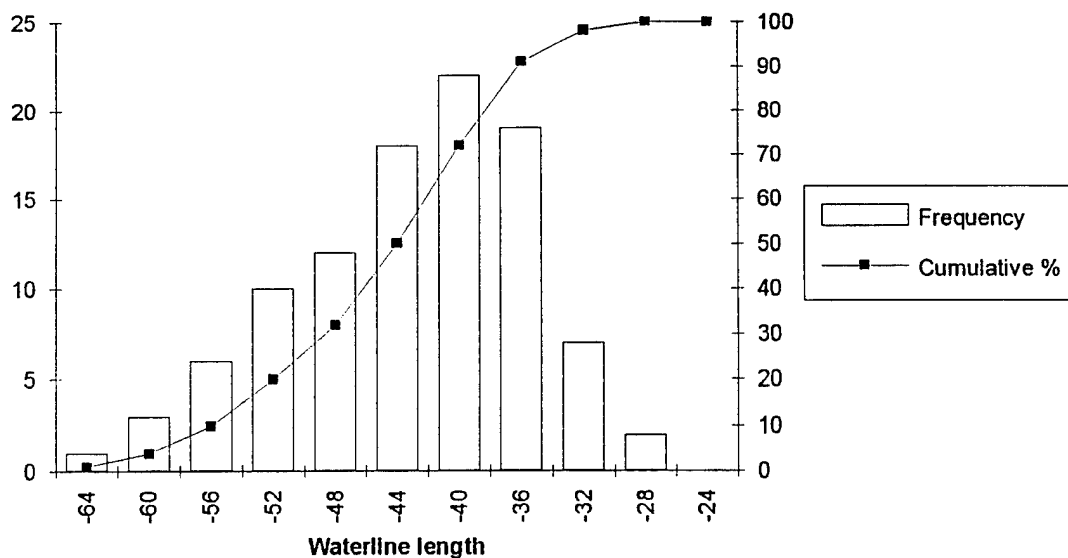
Figure 2. Waterline length for a small iceberg after 14 days melt.

With an initial waterline length of 60 m, a 150% melt deletion policy would set a waterline length of -30 m as the deletion threshold. Under this criterion, 97.9% of the small icebergs would be deleted by the model between ICERECDET patrols.

Similar simulations were conducted for medium and large bergs. The resulting distributions of waterline length were also approximately normally distributed. For

medium bergs (initial waterline length of 122 m), the average waterline length after 28 half days was 12.31 m with a standard deviation of 7.07 m. This means that none of these will have been deleted by the model (waterline length of -61m) by the time of the next patrol, but that most of them will be very difficult to detect. If resighted, they should be classified as a small berg and would be deleted in the next 14 day period. The probability that a medium iceberg will remain a medium iceberg at the next 14 day sighting is less than 10^{-5}.

For large bergs (initial waterline length of 225 m), the average waterline length after 28 half days was 118.1 m with a standard deviation of 6.38 m. As with medium icebergs, none of these will have been deleted by the model (waterline length of -122m) by the time of the next patrol. Approximately 23% will still be classified as large icebergs and the remaining 77% will be classified as medium icebergs.

The above results obviously depend on the nominal values of the input parameters. Clearly, these change over the IIP area of responsibility. In one area a nominal SST of 6°C is reasonable (virtually all observations in the 0-12°C range and two-thirds in the 4-8°C range). In other areas, different values should be used. Nonetheless, the variability represented should more than adequately capture measurement uncertainty. The above analysis suggests that the 150% deletion policy provides good protection against deleting an iceberg prematurely in those areas where the environmental parameters hold and the iceberg drift is such that it remains in the area.

SUMMARY AND CONCLUSIONS

This evaluation and analysis of the IIP iceberg deterioration model has concluded that the model appears to be a very reasonable representation of the deterioration process, with the exception of calving for which meaningful data will be impossible to obtain. This conclusion is supported by our review and that of others described previously. The analytical and empirical sensitivity analyses indicated that sea surface temperature and wave height are very important parameters in the model with respect to their effect on the output (melt rate, time to melt). However, any adverse impacts that errors in these parameters may have are completely overshadowed by the effects of misclassification of the iceberg (wrong specification of the initial waterline length). The simulation analysis indicated that uncertainty in parameter values (including sea surface temperature and wave height) are absorbed by the deletion policy, assuming that the iceberg is correctly classified. Therefore, it does not appear that further refinement of the input environmental variables is required. Any additional effort should be directed toward ensuring a correct initial classification of the icebergs.

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Appendix I. Simulation Evaluation of Iceberg Deletion Policies.

This Appendix includes an analysis of iceberg deletion policies using a Monte Carlo simulation of the IIP iceberg deterioration model. The analysis was conducted by Richard Ashley, Grisselle Centeno, Stephen Joseph, and Lou Tozer at the University of Central Florida, December, 1994. The value of this analysis is as a demonstration of the use of simulation to conduct sensitivity analyses with respect to policy variables of interest. The conclusions drawn in the report are limited by the assumptions stated therein.

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EXECUTIVE SUMMARY

This report gives an overview of the International Ice Patrol (IIP), including its origin, mission, responsibilities, and issuance of the Ice Bulletins and Ice Charts. Also, a description of the flow and determination of information necessary for the execution of the deterioration and drift models is included. An analysis is done on the uncertainty created by the inputs to the deterioration model, how this uncertainty is propagated throughout the model, and how it affects the rules governing the deletion of icebergs from the model. Finally, conclusions based on the analysis are made.

INTRODUCTION

On April 15, 1912, the R.M.S. *Titanic* hit an iceberg and sank in the trans-Atlantic shipping lanes near the Grand Banks off Newfoundland. On January 20, 1914 the International Convention for the Safety of Life at Sea was signed to provide for the establishment of an International Service of Ice Observation and Ice Patrol. The current ice patrol authority is the International Convention for the Safety of Life at Sea (SOLAS). In 1974, SOLAS formed the International Ice Patrol (IIP) to track icebergs and provide warnings to mariners of the potential dangers caused by the presence of these icebergs.

The mission of the IIP is to "determine the Limits of All Known Ice along the southeastern, southern, and southwestern edge of the ice region and publish that information to mariners in a timely fashion".[1] The United States Coast Guard was tasked by SOLAS with the management and operation of the IIP. The area of the IIP's responsibility is from 40°N to 52°N latitude and 39°W to 57°W longitude. Figure 1 shows the area bordered to the west by Newfoundland, Canada and to the northeast by Greenland.

Over 10,000 icebergs are calved from the western coast of Greenland each year. They are then caught in the Labrador Current and carried southward through the Davis Strait and the Labrador Sea to the Grand Banks off the southeast corner of Newfoundland. Flowing north then eastward off the northeast coast of the U.S. is the much warmer Gulf Steam. When these two water currents collide near the Grand Banks, their contrasting temperatures cause dense fog to form nearly half of the year. The IIP aggressively tracks the icebergs that cross south of the 48°N and into the heavily traveled shipping lanes during the iceberg season from March to August.

One of the primary products of the IIP's efforts is the issuance of two daily Ice Bulletins. The 0000Z and 1200Z Ice Bulletins are radio transmissions disseminated at midnight and noon Greenwich Mean Time, respectively. NMF/NIK, the radio station of the U.S. Coast Guard Communications Station in Boston, MA., and VON, the radio station of the Canadian Coast Guard Radio Station at St. John's, Newfoundland, are the primary radio stations responsible for these transmissions. The Bulletins contain the following information: the estimate Limits of All Known Ice, the estimated limit of sea ice, positions of southern and eastern most icebergs, position of growlers, positions of radar targets, and the area of many icebergs. Figure 2 shows an example of a 1200Z Ice Bulletin transmitted July 21, 1994. [1]

The other primary product is the IIP's issuance of the 1200Z Facsimile Chart which depicts the Limits of All Known Ice. The U.S. Coast Guard Communication Station NMF/NIK transmits the ice limits chart at 1600Z and 1810Z (or 4P.M. and 6P.M. Greenwich Mean Time) daily during the iceberg season along with safety messages to warn mariners of icebergs sighted outside of the published ice limits. Figure 3 shows a 1200Z Facsimile Chart transmitted July 21, 1994. [1]

Figure 1: Map of the range of IIP's responsibility

```
NC DE U9
O 202250Z JUL 94
FM COMINTICEPAT GROTON CT
TO AIG EIGHT NINE ONE SIX
CANADIAN COASTAL RADIO STATION ST JOHNS NFLD
MV PAUL BUCK
COMSAT SAFETYNET
     950 L ENFANT PLAZA
     WASHINGTON DC 20024
XMT HMCS HALIFAX
BT
UNCLAS //N16170//
SUBJ: INTERNATIONAL ICE PATROL (IIP) BULLETIN
SECURITE
CCODE/1:31:04:01+1200:00/AOW/IIP/CCODE
1. 211200Z JUL 94 INTERNATIONAL ICE PATROL (IIP) BULLETIN.
REPORT POSITION AND TIME OF ALL ICE SIGHTED TO COMINTICEPAT VIA CG
COMMUNICATIONS STATION NMF, NMN, INMARSAT CODE 42, AND ANY CANADIAN
COAST GUARD RADIO STATION.  ALL SHIPS ARE REQUESTED TO MAKE
UNCLASSIFIED SEA SURFACE TEMPERATURE AND WEATHER REPORTS TO
COMINTICEPAT EVERY SIX HOURS WHEN WITHIN THE LATITUDES OF 40N AND
52N AND LONGITUDES 39W AND 57W.  IT IS NOT NECESSARY TO MAKE THESE
REPORTS IF A ROUTINE WEATHER REPORT IS MADE TO METEO WASHINGTON DC.
ALL MARINERS ARE URGED TO USE EXTREME CAUTION WHEN TRANSITING
NEAR THE GRAND BANKS SINCE ICE MAY BE IN THE AREA.
2. THE ICEBERG, GROWLER, AND RADAR TARGET POSITIONS ARE BASED ON
ESTIMATED DRIFT. DATE OF SIGHTING IS IN PARENTHESIS FOLLOWING THE
POSITION. ALL DATES ARE JULY UNLESS OTHERWISE INDICATED.
3. ESTIMATED LIMIT OF ALL KNOWN ICE: FROM THE NEWFOUNDLAND COAST
NEAR 4635N 5310W TO 4425N 5100W TO 4415N 4700W TO 4500N 4300W TO
5100N 4035W TO 5200N 4100W TO 5700N 5500W THEN EASTWARD.
THE ICEBERG LIMIT NORTH OF 52N IS OBTAINED FROM ENVIRONMENT
CANADA'S ICE CENTER OTTAWA.
4. NO SEA ICE SOUTH OF 52N.
5. SOUTHERN AND EASTERN MOST BERGS ESTIMATED AT: 4550N 4338W(16),
4459N 4738W(15), 4450N 4743W(15), 4450N 4744W(15), 4536N 4358W(12),
5114N 4134W(12), 4633N 4313W(06), 4454N 4817W(17).
6. RADAR TARGETS ESTIMATED AT: 4721N 4358W(18), 4718N 4356W(18).
7. THE FOLLOWING RADAR TARGETS ARE OUTSIDE THE LIMITS OF
ALL KNOWN ICE: 4627N 5415W(19), 4609N 5330W(19), 4705N 3830W(14).
8. THERE ARE MANY ICEBERGS AND GROWLERS NORTH OF 4500N AND WEST
OF 4400W WITHIN THE LIMITS OF ALL KNOWN ICE.
BT
```

Figure 2: 211200Z JUL 94 International Ice Patrol (IIP) Bulletin
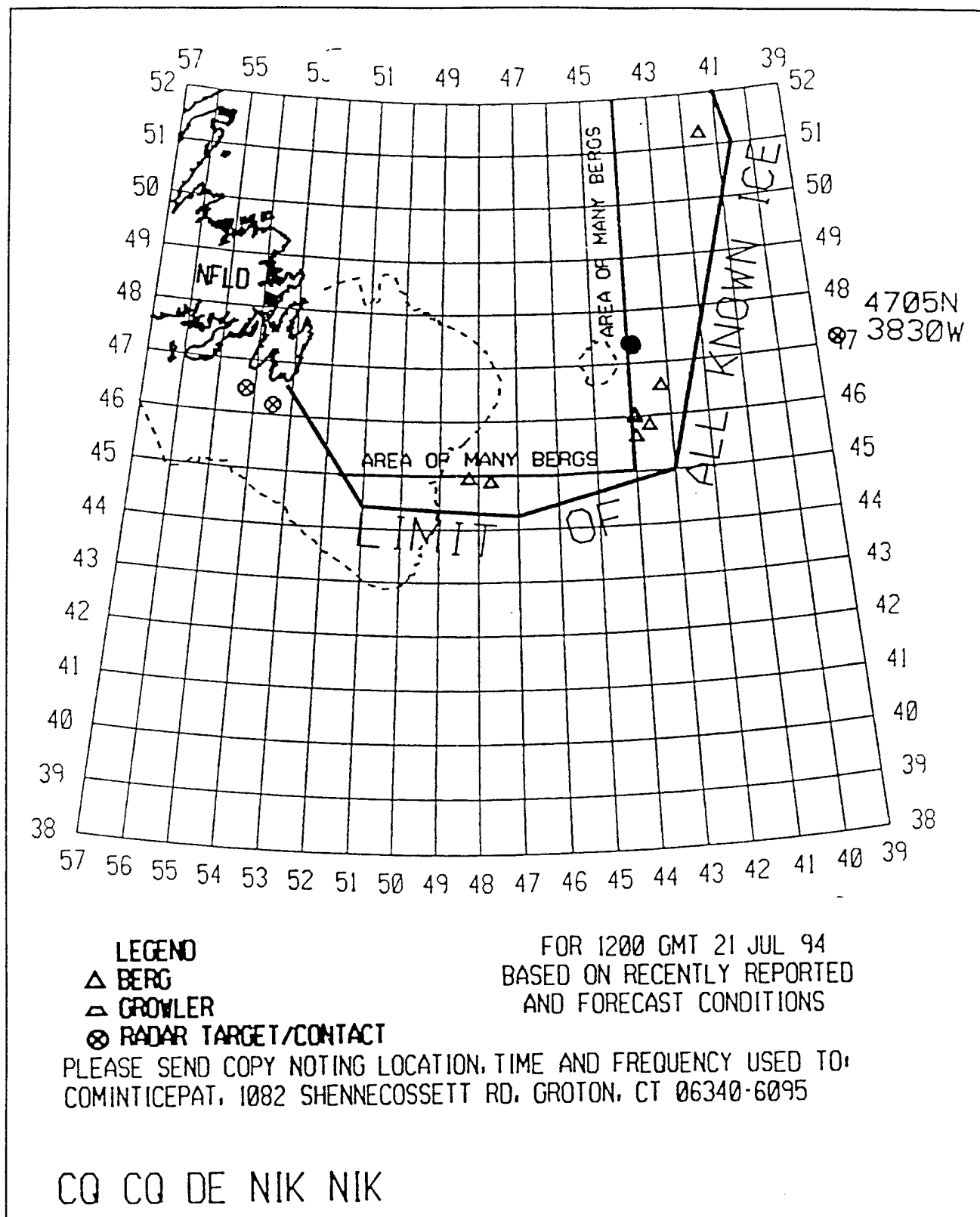
Figure 3: 1200 GMT 21 JUL 94 International Ice Patrol (IIP) Facsimile Chart
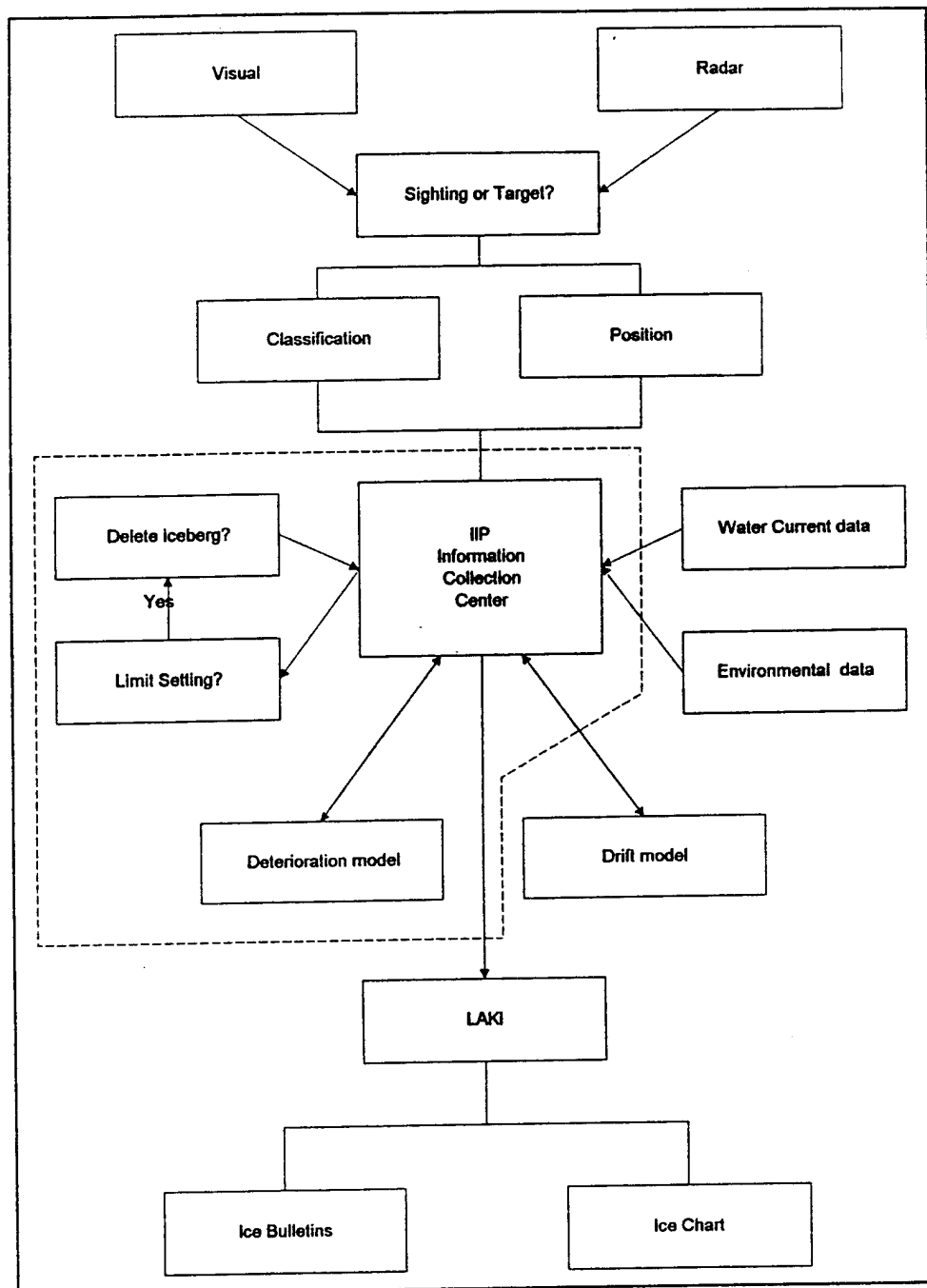
Figure 4: Overall Process Information Flow

LAKI PROCESS DESCRIPTION

The IIP determines the LAKI using many different sources of information in the generation of the Ice Bulletins and the Ice Chart. See Figure 4 for the information flow. A description of the input information follows.

Size and shape classification

- Over 60% of the data is radar based.

- Less than 40% are visual sightings received from ships operating in the area.

- Four categories for size: growler, small, medium and large (the iceberg is assumed to be medium when it is considered a target iceberg).

- Two categories for shape: tabular, non tabular (the iceberg is assumed to be non-tabular when it is considered a target iceberg).

Environmental information

- This information is received primarily from U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC).

- The information includes: surface wind, wave height, wave period, sea surface temperature.

Water current information

- This information includes: Geostrophic mean historical current, and real-time (local) received from drift buoys tracked by satellite.

200% Side Looking Airborne Radar (SLAR)

- The Ice Reconnaissance Detachment (ICERECDET) conducts a 200% surveillance of the area every 14 days. This information is used to update the positions of the known icebergs, to add any icebergs not already detected, and as a criteria for the deletion of an iceberg.

The IIP Information Collection Center (ICC) uses these as inputs to the Drift and Deterioration Models described below.

Drift model

- Inputs used: local wind, position, size and shape, geostrophic current, local current.

- Description: The drift model updates the position of the icebergs as they move through the area of the IIP responsibility.

Deterioration model

- Inputs used: position, size, sea surface temperature, wave height, wave period.

- Ways of deterioration: insulation (sun heating), buoyant convection (vertical circulation of the water), wind force convection (drift movement through the water), wave induced (wave washing of the subaerial surface).

- Deletion criteria: The iceberg is deleted from the database of all known icebergs if 125% of the original waterline length has melted. If the iceberg is a limit setting iceberg then it is retained in the model until 150% of its waterline length has melted.

- Description: Predicts the degree of iceberg linear surface length melt.

IIP produce the Ice Bulletins and Ice Chart only after the Deterioration and Drift Models output is sent back to the ICC and combined with all inputs.

Final Outputs

- Ice Bulletins: See Figure 2 for an example of an Ice Bulletin.

- Ice Chart: See Figure 3 for an example of an Ice Chart.
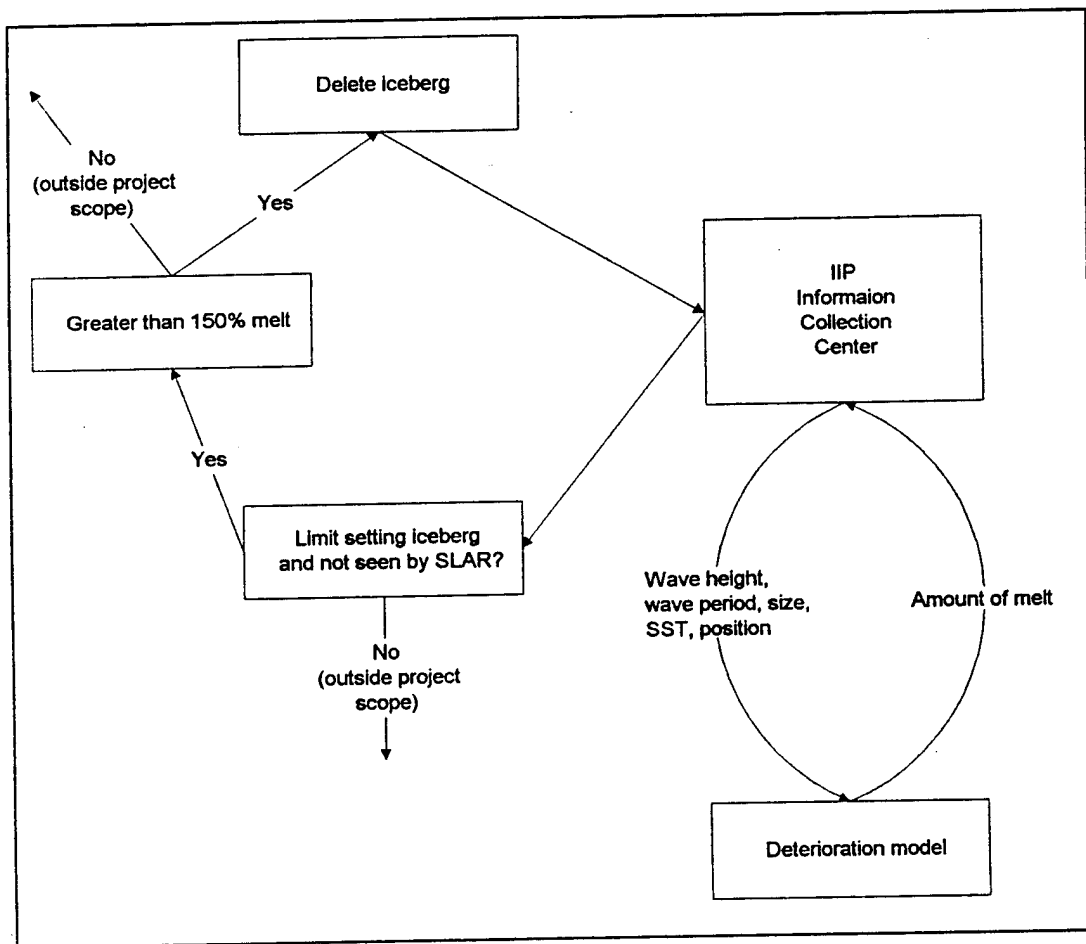
Figure 5: Project Information Flow

PROJECT OBJECTIVE

The main objective of the project is to verify, within 99% confidence, that 150% melt criteria for the limit setting icebergs is a reliable policy decision for deleting an iceberg from the overall iceberg database. Figure 4 shows the overall information flow for the generation of the LAKI Ice Bulletins and Ice Charts. The dashed portion, detailed in Figure 5, represents the information flow of the area where this objective is applied.

PROJECT ASSUMPTIONS

The following assumptions were drawn in the analysis of the deletion criteria.

- The icebergs are always melting.

- A limit setting iceberg is defined as an iceberg within 60nm north and east of the LAKI, or any location south and west of the LAKI. The project only considers these icebergs which are consider to stay within this limit setting area throughout the analysis.

- The water length used in the Monte Carlo simulation is the maximum waterline length for the small, medium, and large size icebergs.

- It is assumed that the 200% SLAR coverage at the end of the 28th half day did not see the simulated icebergs. This assumption along with the use of only limit setting icebergs is important because if an existing limit setting iceberg is missed by the reconnaissance and deleted, the result could be catastrophic.

- A Monte Carlo simulation is run for 28 half days (14 days), this time is considered discrete time

- All input variables for the Monte Carlo simulation model are independent and normally distributed, except for the size of the iceberg.

UNCERTAINTY

There is uncertainty involved at all levels of the LAKI process. A considerable amount of information that serves as inputs for the drift and deterioration models are derived from a historical database. This along with measuremental errors contributes to the uncertainty associated with the models' input parameters.

Other sources of uncertainty are associated with the initial classifications of the icebergs. For example, if the size is not known, then it is assumed to be medium. As a result of uncertainties in the inputs, the model outputs are also uncertain. The propagation of uncertainty per half day associated with the deterioration model is shown in Figure 6. There is also uncertainty associated with position, which is both an input, and an output of the drift model.

In order to compensate for positional uncertainty the IIP uses error circles which increase in diameter over time. This rule also takes into account the iceberg splitting. The IIP also uses the 125% and 150% melt criteria for deletion which means that an iceberg must melt to a negative waterline length before it is deleted from the all known iceberg database.

These uncertainties contribute to the risk of collisions between ships and icebergs potentially causing human and monetary losses. Therefore they must be taken under serious consideration.
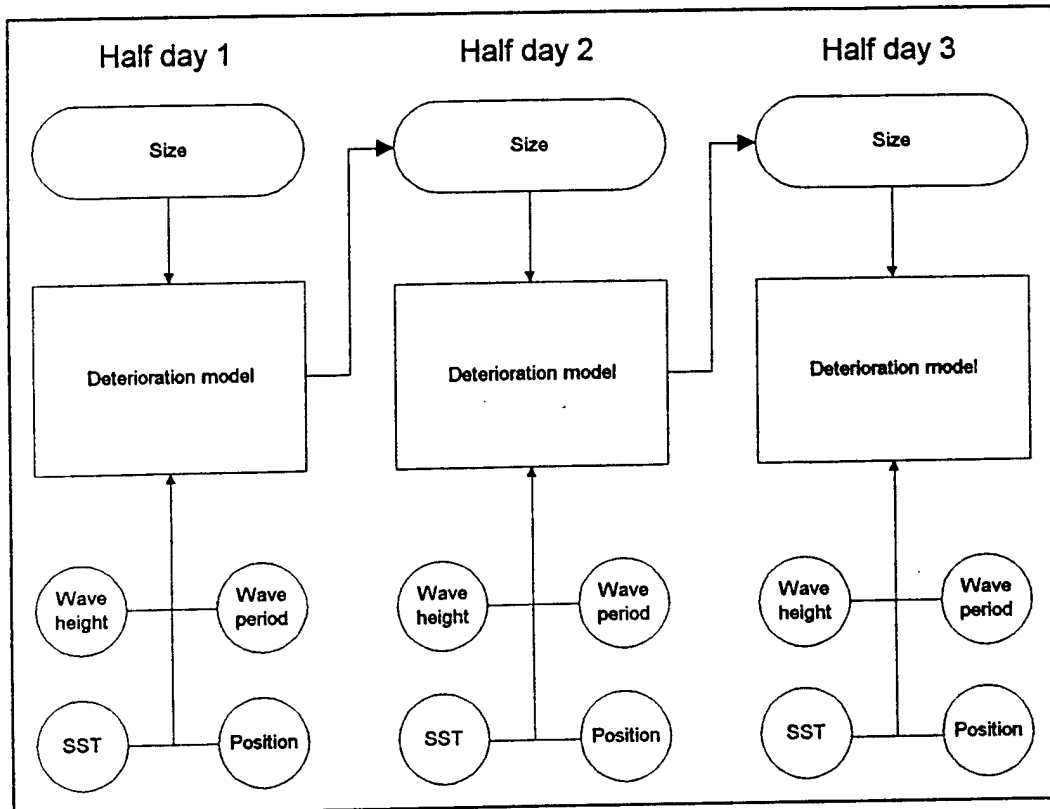
Figure 6: Influence Diagram Showing Propagation of Error in the Deteriroation Model

METHODOLOGY

Uncertainties in input parameters were propagated through the deterioration model using a Monte Carlo Simulation. This method was chosen because imprecisions in the propagated output distribution and measures of uncertainty are easily estimated. There is also no need to discretize the distributions as required by other methods. Improvement can be achieved by taking more samples [5].

Once a preliminary univariate parametric sensitivity and uncertainty analysis was performed [2], the factors contributing most to output uncertainty were identified. All input distributions are considered normal. All input variables are randomly generated and

are assumed independent. The base case values were used as expected values for the input variables. The plausible uncertainties in the input variables were used to determine the standard deviations.

The predicted melt for waterline lengths of 60m, 122m, and 225m, was computed using normally distributed random variables. This melt was subtracted from the previous length and used as the new length. Then another set of random variables were generated to compute the next half day's melt. This allows for the combination of errors over all iterations. This was repeated for a total of 28 intervals corresponding to 14 days. These iterations constituted one simulation run (see Appendix II for spreadsheet, and Appendix III for simulation code).

A total of 100 simulation runs were performed for each size. The melt was combined into intervals for a histogram to determine the distribution. This was then verified with the goodness of fit using the chi-square. The uncertainty in the output distribution represents the uncertainty associated with iceberg melt for specific initial lengths. The quantification of these errors allows for the determination of a value for the percent melt that should be used as a criterion for iceberg deletion.

RESULTS

The results for the 100 runs for the small, medium and large icebergs can be found in Appendix I. For each size iceberg descriptive statistics were generated, they are shown in Tables 1, 5, and 9 . A histogram was plotted to help identify the proper modeling distribution (See Figures 7, 8, and 9). For all cases a normal distribution appeared to be appropriate. Based on the normal distribution, the distribution parameters from the descriptive statistics were used to develop theoretical frequencies. This was compared with the actual frequencies to determine Chi-Squared values for a Goodness-of-Fit test. These results can be found in Tables 2, 6, and 10.

A 99% upper confidence interval on the standard deviation was generated for each size iceberg. The results can be found in Tables 3, 7, and 11. These upper confidence limits were used to calculate the uncertainty in melt for each given size. To allow for an iceberg to be deleted, the iceberg must be melted to a size of zero plus the uncertainty. Finally, this is shown as % melt in Tables 4, 8, and 12 for several probabilities of existence.

For Size 60 Berg

Descriptive Statistics	
	.
Mean	-45.17
Standard Error	0.746218
Median	-43.8747
Standard Deviation	7.46218
Sample Variance	55.68412
Kurtosis	-0.42814
Skewness	-0.42338
Range	33.59649
Minimum	-64.242
Maximum	-30.6455
Sum	-4517
Count	100
Largest(1)	-30.6455
Smallest(1)	-64.242

Table 1: Small Iceberg Melted Size Statistics
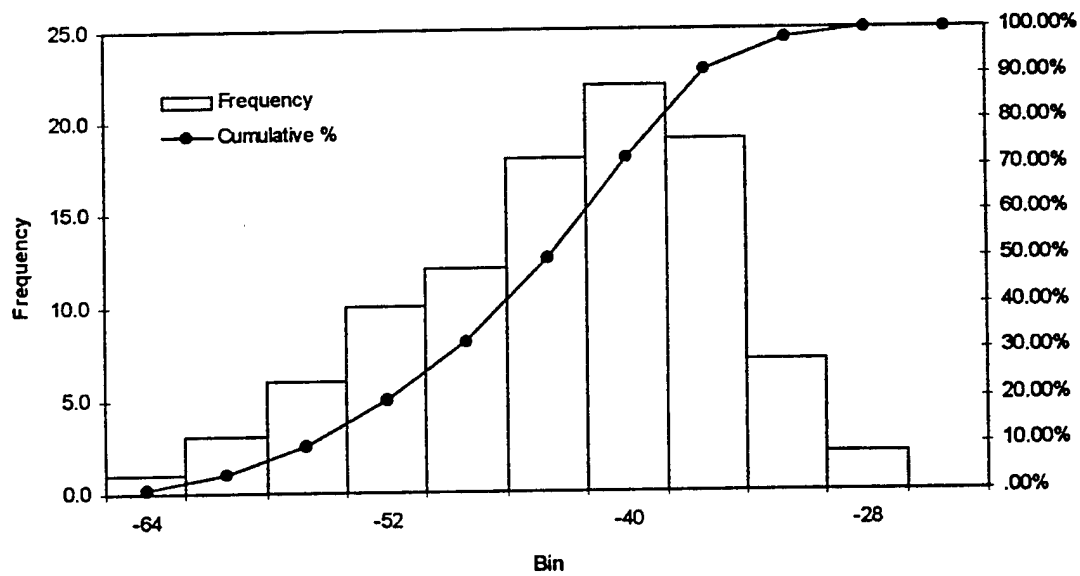
Histogram

Figure 7: Small Iceberg Melted Size Histogram

For Size 60 Berg

Bin	Frequency	Cumulative %	Theor. Cumulative %	Theor. Frequency	Chi-Square
-64	1	1.00%	.58%	0.58	0.30
-60	3	4.00%	2.34%	1.76	0.87
-56	6	10.00%	7.33%	4.99	0.20
-52	10	20.00%	18.00%	10.67	0.04
-48	12	32.00%	35.23%	17.22	1.58
-44	18	50.00%	56.23%	21.00	0.43
-40	22	72.00%	75.58%	19.35	0.36
-36	19	91.00%	89.04%	13.46	2.28
-32	7	98.00%	96.12%	7.08	0.00
-28	2	100.00%	98.93%	2.81	0.23
-24	0	100.00%	100.00%	1.07	1.07
				Total -->	7.37
				Chi-Square(.05,8) -->	**15.51**

Table 2: Small Iceberg Goodness of Fit with Normal

For Size 60 Berg

S^2	α	Upper C.I. S^2	Upper C.I. S
55.68	1.00%	79.63	8.92

Table 3: Small Iceberg 99% Confidence Interval on Standard Deviation

For Size 60 Berg

P Existing	Average	Upper Limit	Delta Melt (error)	% melt
.50%	-45.17	-22.18	22.99	138.31%
1.00%	-45.17	-24.41	20.76	134.60%
1.50%	-45.17	-25.81	19.36	132.27%
2.00%	-45.17	-26.84	18.33	130.54%
2.50%	-45.17	-27.68	17.49	129.15%
3.00%	-45.17	-28.39	16.78	127.97%

Table 4: Probability of the Existence of a Small Iceberg v.s. % Melt

For Size 122 Berg

Descriptive Statistics	
Mean	12.31291
Standard Error	0.706614
Median	13.12535
Standard Deviation	7.066138
Sample Variance	49.93031
Kurtosis	-0.53565
Skewness	-0.13874
Range	31.6613
Minimum	-2.89096
Maximum	28.77034
Sum	1231.291
Count	100
Largest(1)	28.77034
Smallest(1)	-2.89096

Table 5: Medium Iceberg Melted Size Statistics
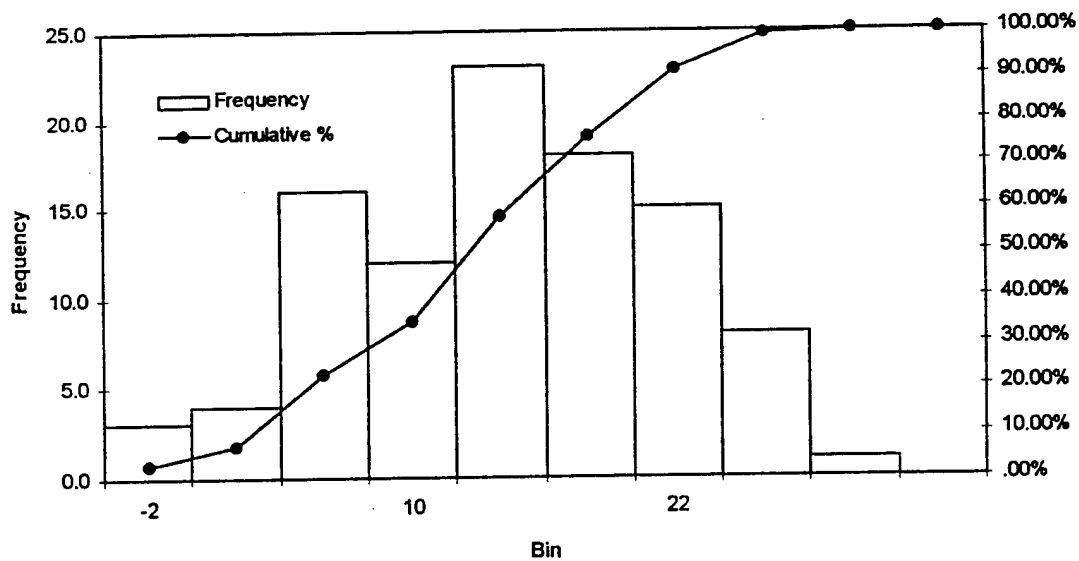
Histogram

Figure 8: Medium Iceberg Melted Size Histogram

For Size 122 Berg

Bin	Frequency	Cumulative %	Theor. Cumulative %	Theor. Frequency	Chi-Square
-2	3	3.00%	2.14%	2.14	0.35
2	4	7.00%	7.22%	5.08	0.23
6	16	23.00%	18.58%	11.36	1.89
10	12	35.00%	37.17%	18.59	2.34
14	23	58.00%	59.44%	22.26	0.02
18	18	76.00%	78.95%	19.52	0.12
22	15	91.00%	91.48%	12.53	0.49
26	8	99.00%	97.36%	5.88	0.76
30	1	100.00%	99.38%	2.02	0.52
34	0	100.00%	99.89%	0.51	0.51
				Total -->	7.22

Chi-Square(.05,8) --> **14.07**

Table 6: Medium Iceberg Goodness of Fit with Normal

For Size 122 Berg

S^2	α	Upper C.I. S^2	Upper C.I. S
49.93	1.00%	71.40	8.45

Table 7: Medium Iceberg 99% Confidence Interval on Standard Deviation

For Size 122 Berg

P Existing	Average	Upper Limit	Delta Melt (error)	% melt
.50%	12.31	34.08	21.77	117.84%
1.00%	12.31	31.97	19.66	116.11%
1.50%	12.31	30.65	18.34	115.03%
2.00%	12.31	29.67	17.35	114.22%
2.50%	12.31	28.87	16.56	113.58%
3.00%	12.31	28.21	15.89	113.03%

Table 8: Probability of the Existence of a Medium Iceberg v.s. % Melt

For Size 225 Berg

Descriptive Statistics	
Mean	118.1247
Standard Error	0.638016
Median	118.1752
Standard Deviation	6.380162
Sample Variance	40.70647
Kurtosis	-0.34303
Skewness	-0.15544
Range	28.07099
Minimum	102.0398
Maximum	130.1108
Sum	11812.47
Count	100
Largest(1)	130.1108
Smallest(1)	102.0398

Table 9: Large Iceberg Melted Size Statistics
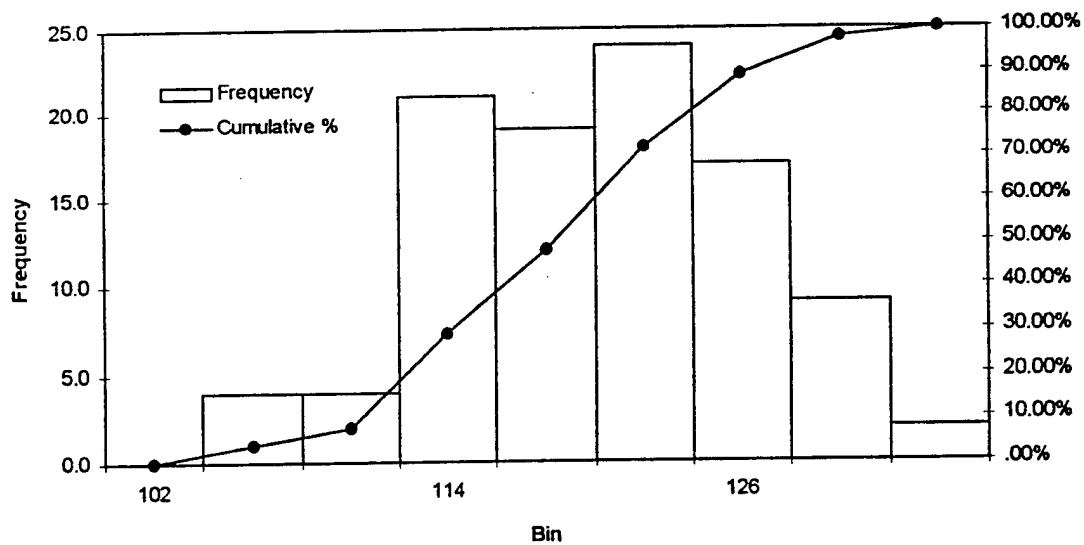
Histogram

Figure 9: Large Iceberg Melted Size Histogram

For Size 225 Berg

Bin	Frequency	Cumulative %	Theor. Cumulative %	Theor. Frequency	Chi- Square
102	0	.00%	.57%	0.57	0.57
106	4	4.00%	2.87%	2.29	1.27
110	4	8.00%	10.14%	7.27	1.47
114	21	29.00%	25.90%	15.75	1.75
118	19	48.00%	49.22%	23.32	0.80
122	24	72.00%	72.82%	23.60	0.01
126	17	89.00%	89.15%	16.33	0.03
130	9	98.00%	96.86%	7.72	0.21
134	2	100.00%	99.36%	2.49	0.10
				Total —>	6.21

Chi-Square(.05,8) —>   **14.07**

Table 10: Large Iceberg Goodness of Fit with Normal

For Size 225 Berg

S^2	α	Upper C.I. S^2	Upper C.I. S
40.71	1.00%	58.21	7.63

Table 11: Large Iceberg 99% Confidence Interval on Standard Deviation

For Size 225 Berg

P Existing	Average	Upper Limit	Delta Melt (error)	% melt
.50%	118.12	137.78	19.65	108.73%
1.00%	118.12	135.87	17.75	107.89%
1.50%	118.12	134.68	16.56	107.36%
2.00%	118.12	133.79	15.67	106.96%
2.50%	118.12	133.08	14.95	106.65%
3.00%	118.12	132.47	14.35	106.38%

Table 12: Probability of the Existence of a Large Iceberg v.s. % Melt

CONCLUSION

It has been assumed that the icebergs in the model have not been located by the SLAR. Based on this assumption and the uncertainty determined by the simulation model, IIP's 150% melt policy is a conservative policy when run for 28 half days for any size iceberg. For example, to insure an iceberg is melted, it must melt 100% plus the uncertainty. The simulation model shows that this would result in a 138% melt for small icebergs instead of the existing policy of 150% melt.

Current policy states that if the SLAR resighting is a target, the current deterioration model size is used. This results in the further propagation of the uncertainty. To study this, a simulation was run for 56 half days on medium icebergs with the results indicating an increase of 45.7% on the standard deviation. If there are a large number of medium icebergs that are resighted as targets, this percent change could significantly influence the policy.

The uncertainty in melt for each size is approximately the same. (At a probability of 0.5%, the small iceberg uncertainty was 22.99 m, 21.77 m for medium, and 19.65 m for large icebergs.) Therefore, it is believed that the policy of using 150% melt for each size iceberg is extremely conservative especially for the larger icebergs.

By lowering the melt percent, the mariners cost could potentially be reduced without increasing the potential danger of iceberg collision, if the area of the LAKI could be reduced. This may be a good area for further consideration. For example, a policy of 138% for small, 117% for medium, and 108% for large icebergs.

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APPENDIX I

Simulation results of 100 runs for small, medium, and large icebergs.

For Size 60 Berg

Run	Start Size	New Size	Melt	% Melt
1	60	-47.1	107.1	178%
2	60	-41.5	101.5	169%
3	60	-54.8	114.8	191%
4	60	-36.6	96.6	161%
5	60	-42.0	102.0	170%
6	60	-61.3	121.3	202%
7	60	-42.9	102.9	171%
8	60	-40.7	100.7	168%
9	60	-41.4	101.4	169%
10	60	-40.8	100.8	168%
11	60	-39.1	99.1	165%
12	60	-46.3	106.3	177%
13	60	-53.3	113.3	189%
14	60	-36.6	96.6	161%
15	60	-42.7	102.7	171%
16	60	-48.8	108.8	181%
17	60	-56.3	116.3	194%
18	60	-35.5	95.5	159%
19	60	-55.7	115.7	193%
20	60	-47.7	107.7	180%
21	60	-51.5	111.5	186%
22	60	-49.0	109.0	182%
23	60	-41.0	101.0	168%
24	60	-39.6	99.6	166%
25	60	-44.2	104.2	174%
26	60	-53.2	113.2	189%
27	60	-57.4	117.4	196%
28	60	-34.4	94.4	157%
29	60	-39.3	99.3	166%
30	60	-53.6	113.6	189%
31	60	-38.3	98.3	164%
32	60	-43.2	103.2	172%
33	60	-39.4	99.4	166%
34	60	-41.1	101.1	168%
35	60	-58.7	118.7	198%
36	60	-47.1	107.1	179%
37	60	-51.0	111.0	185%
38	60	-46.9	106.9	178%
39	60	-46.8	106.8	178%
40	60	-39.3	99.3	166%
41	60	-64.2	124.2	207%
42	60	-49.2	109.2	182%
43	60	-41.1	101.1	168%
44	60	-38.3	98.3	164%
45	60	-48.8	108.8	181%
46	60	-42.7	102.7	171%
47	60	-55.0	115.0	192%
48	60	-47.8	107.8	180%
49	60	-52.6	112.6	188%
50	60	-45.1	105.1	175%

51	60	-46.0	106.0	177%
52	60	-40.0	100.0	167%
53	60	-51.1	111.1	185%
54	60	-48.3	108.3	180%
55	60	-40.6	100.6	168%
56	60	-61.2	121.2	202%
57	60	-46.4	106.4	177%
58	60	-41.8	101.8	170%
59	60	-56.6	116.6	194%
60	60	-54.4	114.4	191%
61	60	-38.9	98.9	165%
62	60	-33.5	93.5	156%
63	60	-43.7	103.7	173%
64	60	-30.6	90.6	151%
65	60	-33.7	93.7	156%
66	60	-47.4	107.4	179%
67	60	-37.8	97.8	163%
68	60	-58.9	118.9	198%
69	60	-48.8	108.8	181%
70	60	-36.2	96.2	160%
71	60	-34.4	94.4	157%
72	60	-41.9	101.9	170%
73	60	-42.8	102.8	171%
74	60	-45.0	105.0	175%
75	60	-42.5	102.5	171%
76	60	-44.8	104.8	175%
77	60	-34.8	94.8	158%
78	60	-52.3	112.3	187%
79	60	-39.7	99.7	166%
80	60	-50.7	110.7	185%
81	60	-44.0	104.0	173%
82	60	-47.9	107.9	180%
83	60	-30.9	90.9	151%
84	60	-48.0	108.0	180%
85	60	-49.2	109.2	182%
86	60	-60.1	120.1	200%
87	60	-40.2	100.2	167%
88	60	-51.6	111.6	186%
89	60	-58.3	118.3	197%
90	60	-38.3	98.3	164%
91	60	-38.4	98.4	164%
92	60	-43.3	103.3	172%
93	60	-39.2	99.2	165%
94	60	-39.8	99.8	166%
95	60	-45.1	105.1	175%
96	60	-34.6	94.6	158%
97	60	-53.5	113.5	189%
98	60	-42.0	102.0	170%
99	60	-38.1	98.1	163%
100	60	-39.0	99.0	165%

For Size 122 Berg

Run	Start Size	New Size	Melt	% Melt
1	122	21.5	100.5	82%
2	122	5.2	116.8	96%
3	122	11.4	110.6	91%
4	122	10.9	111.1	91%
5	122	18.6	103.4	85%
6	122	8.5	113.5	93%
7	122	3.4	118.6	97%
8	122	14.7	107.3	88%
9	122	8.8	113.2	93%
10	122	0.7	121.3	99%
11	122	16.6	105.4	86%
12	122	9.8	112.2	92%
13	122	4.2	117.8	97%
14	122	14.8	107.2	88%
15	122	2.1	119.9	98%
16	122	15.6	106.4	87%
17	122	13.6	108.4	89%
18	122	14.5	107.5	88%
19	122	14.5	107.5	88%
20	122	28.8	93.2	76%
21	122	16.4	105.6	87%
22	122	18.0	104.0	85%
23	122	13.4	108.6	89%
24	122	12.6	109.4	90%
25	122	22.2	99.8	82%
26	122	5.5	116.5	96%
27	122	11.4	110.6	91%
28	122	3.5	118.5	97%
29	122	25.0	97.0	79%
30	122	12.1	109.9	90%
31	122	14.7	107.3	88%
32	122	8.0	114.0	93%
33	122	12.3	109.7	90%
34	122	18.3	103.7	85%
35	122	23.6	98.4	81%
36	122	15.5	106.5	87%
37	122	13.2	108.8	89%
38	122	23.6	98.4	81%
39	122	19.8	102.2	84%
40	122	22.1	99.9	82%
41	122	9.6	112.4	92%
42	122	13.2	108.8	89%
43	122	15.9	106.1	87%
44	122	8.4	113.6	93%
45	122	2.1	119.9	98%
46	122	10.8	111.2	91%
47	122	18.0	104.0	85%
48	122	4.6	117.4	96%
49	122	15.8	106.2	87%
50	122	25.9	96.1	79%
51	122	4.6	117.4	96%
52	122	14.9	107.1	88%
53	122	3.0	119.0	98%
54	122	11.4	110.6	91%
55	122	20.2	101.8	83%
56	122	22.2	99.8	82%
57	122	22.8	99.2	81%
58	122	15.9	106.1	87%
59	122	11.2	110.8	91%
60	122	9.4	112.6	92%
61	122	19.9	102.1	84%
62	122	9.1	112.9	93%
63	122	11.5	110.5	91%
64	122	15.7	106.3	87%
65	122	-0.3	122.3	100%
66	122	-2.7	124.7	102%
67	122	15.8	106.2	87%
68	122	21.8	100.2	82%
69	122	17.4	104.6	86%
70	122	-2.9	124.9	102%
71	122	4.9	117.1	96%
72	122	3.8	118.2	97%
73	122	3.7	118.3	97%
74	122	4.7	117.3	96%
75	122	13.6	108.4	89%
76	122	21.3	100.7	83%
77	122	18.2	103.8	85%
78	122	-2.1	124.1	102%
79	122	13.5	108.5	89%
80	122	11.9	110.1	90%
81	122	-1.3	123.3	101%
82	122	13.2	108.8	89%
83	122	10.0	112.0	92%
84	122	13.8	108.2	89%
85	122	21.1	100.9	83%
86	122	9.6	112.4	92%
87	122	13.1	108.9	89%
88	122	18.1	103.9	85%
89	122	18.3	103.7	85%
90	122	10.2	111.8	92%
91	122	7.1	114.9	94%
92	122	11.2	110.8	91%
93	122	7.6	114.4	94%
94	122	14.9	107.1	88%
95	122	18.3	103.7	85%
96	122	3.3	118.7	97%
97	122	21.1	100.9	83%
98	122	9.2	112.8	92%
99	122	1.9	120.1	98%
100	122	2.1	119.9	98%

For Size 225 Berg

Run	Start Size	New Size	Melt	% Melt
1	225	117.5	107.5	48%
2	225	112.9	112.1	50%
3	225	121.8	103.2	46%
4	225	121.6	103.4	46%
5	225	118.1	106.9	48%
6	225	115.6	109.4	49%
7	225	104.0	121.0	54%
8	225	122.2	102.8	46%
9	225	121.1	103.9	46%
10	225	128.9	96.1	43%
11	225	108.2	116.8	52%
12	225	117.8	107.2	48%
13	225	110.8	114.2	51%
14	225	116.7	108.3	48%
15	225	129.4	95.6	42%
16	225	115.8	109.2	49%
17	225	125.8	99.2	44%
18	225	124.4	100.6	45%
19	225	120.5	104.5	46%
20	225	118.3	106.7	47%
21	225	109.8	115.2	51%
22	225	119.1	105.9	47%
23	225	115.9	109.1	48%
24	225	112.8	112.2	50%
25	225	109.5	115.5	51%
26	225	122.0	103.0	46%
27	225	125.5	99.5	44%
28	225	120.4	104.6	46%
29	225	115.8	109.2	49%
30	225	125.8	99.2	44%
31	225	118.8	106.2	47%
32	225	124.6	100.4	45%
33	225	113.8	111.2	49%
34	225	116.7	108.3	48%
35	225	118.0	107.0	48%
36	225	126.0	99.0	44%
37	225	128.3	96.7	43%
38	225	127.4	97.6	43%
39	225	113.7	111.3	49%
40	225	129.6	95.4	42%
41	225	117.9	107.1	48%
42	225	123.6	101.4	45%
43	225	113.0	112.0	50%
44	225	110.9	114.1	51%
45	225	114.8	110.2	49%
46	225	103.0	122.0	54%
47	225	118.8	106.2	47%
48	225	111.8	113.2	50%
49	225	124.8	100.2	45%
50	225	113.0	112.0	50%

Run	Start Size	New Size	Melt	% Melt
51	225	123.8	101.2	45%
52	225	112.2	112.8	50%
53	225	114.2	110.8	49%
54	225	122.7	102.3	45%
55	225	102.0	123.0	55%
56	225	118.6	106.4	47%
57	225	122.2	102.8	46%
58	225	110.0	115.0	51%
59	225	119.7	105.3	47%
60	225	111.7	113.3	50%
61	225	114.3	110.7	49%
62	225	116.3	108.7	48%
63	225	122.9	102.1	45%
64	225	119.2	105.8	47%
65	225	111.4	113.6	51%
66	225	106.2	118.8	53%
67	225	113.9	111.1	49%
68	225	122.9	102.1	45%
69	225	128.7	96.3	43%
70	225	110.9	114.1	51%
71	225	119.5	105.5	47%
72	225	130.1	94.9	42%
73	225	120.4	104.6	46%
74	225	123.4	101.6	45%
75	225	121.7	103.3	46%
76	225	130.1	94.9	42%
77	225	113.4	111.6	50%
78	225	112.9	112.1	50%
79	225	120.3	104.7	47%
80	225	119.6	105.4	47%
81	225	124.4	100.6	45%
82	225	118.5	106.5	47%
83	225	112.4	112.6	50%
84	225	121.0	104.0	46%
85	225	115.0	110.0	49%
86	225	123.1	101.9	45%
87	225	114.3	110.7	49%
88	225	120.4	104.6	47%
89	225	112.8	112.2	50%
90	225	113.5	111.5	50%
91	225	114.1	110.9	49%
92	225	117.1	107.9	48%
93	225	127.3	97.7	43%
94	225	117.9	107.1	48%
95	225	120.7	104.3	46%
96	225	105.5	119.5	53%
97	225	110.7	114.3	51%
98	225	126.2	98.8	44%
99	225	128.6	96.4	43%
100	225	116.7	108.3	48%

Simulation spreadsheet example for the 28 half days.

	Distribution Parameters for Input Variables										Iceberg Size -->	122
Mean	182.9	6		10	25					Number of Simulation Runs -->		100
Std	30	2		1.66	3.33							
Half Days	Wave Height	Sea Surface Temp.	Water Line Length	Wave Period	Relative Speed	Time In Half Days	Components of Melt Model					Answer
hDay	xamp	SST	rlen	iper	relspd	ztime	fc	sun	buoy	winfo	wave	melt
1	156.2	4.9	-95.3	8.8	25.8	1	0.00	0.01	0.05	0.00	2.77	2.83
2	180.3	8.5	-98.1	9.2	23.2	1	0.00	0.01	0.09	0.00	4.76	4.86
3	210.3	6.2	-103.0	11.3	21.9	1	0.00	0.01	0.06	0.00	3.35	3.42
4	161.9	7.1	-106.4	9.3	20.1	1	0.00	0.01	0.07	0.00	3.66	3.75
5	215.1	5.5	-110.1	9.5	32.2	1	0.00	0.01	0.05	0.00	3.67	3.73
6	198.0	5.8	-113.9	9.2	21.4	1	0.00	0.01	0.06	0.00	3.64	3.71
7	138.0	6.4	-117.6	10.1	23.7	1	0.00	0.01	0.06	0.00	2.75	2.82
8	153.8	9.8	-120.4	10.6	22.9	1	0.00	0.01	0.12	0.00	4.14	4.27
9	193.9	3.5	-124.6	11.5	21.8	1	0.00	0.01	0.03	0.00	1.93	1.97
10	190.6	4.4	-126.6	9.7	29.3	1	0.00	0.01	0.04	0.00	2.68	2.72
11	202.7	4.2	-129.3	10.1	28.3	1	0.00	0.01	0.04	0.00	2.58	2.63
12	226.8	4.6	-132.0	9.0	22.0	1	0.00	0.01	0.04	0.00	3.45	3.50
13	173.8	7.8	-135.5	8.4	19.0	1	0.00	0.01	0.08	0.00	4.71	4.81
14	175.3	8.1	-140.3	9.2	25.3	1	0.00	0.01	0.09	0.00	4.50	4.60
15	143.9	5.5	-144.9	8.9	18.4	1	0.00	0.01	0.05	0.00	2.82	2.89
16	212.5	3.9	-147.8	10.3	21.0	1	0.00	0.01	0.03	0.00	2.50	2.55
17	222.0	10.1	-150.3	7.9	26.1	1	0.00	0.01	0.12	0.00	7.69	7.82
18	182.8	7.3	-158.1	12.4	26.2	1	0.00	0.01	0.08	0.00	3.13	3.22
19	183.9	7.3	-161.4	11.1	23.5	1	0.00	0.01	0.08	0.00	3.52	3.60
20	151.8	6.8	-165.0	8.7	26.5	1	0.00	0.01	0.07	0.00	3.62	3.70
21	220.3	3.7	-168.7	7.8	22.2	1	0.00	0.01	0.03	0.00	3.30	3.34
22	194.4	5.8	-172.0	10.8	23.6	1	0.00	0.01	0.06	0.00	3.09	3.16
23	158.0	4.4	-175.2	11.7	28.9	1	0.00	0.01	0.04	0.00	1.94	1.99
24	170.9	4.3	-177.1	9.6	18.3	1	0.00	0.01	0.04	0.00	2.46	2.51
25	175.9	1.9	-179.7	8.2	24.5	1	0.00	0.01	0.02	0.00	1.62	1.65
26	194.9	7.6	-181.3	11.0	22.7	1	0.00	0.01	0.08	0.00	3.86	3.96
27	151.7	4.6	-185.3	10.0	27.2	1	0.00	0.01	0.04	0.00	2.26	2.32
28	142.7	4.5	-187.6	11.5	30.2	1	0.00	0.01	0.04	0.00	1.84	1.90

APPENDIX III

Simulation program.

```vb
' Simulate Macro
' Macro recorded 11/19/94 by Richard Ashley
'
'
Sub Simulate()
For I = 1 To Cells(3, "O")
  Range("F6").Value = Range(Cells(I + 4, "R"), Cells(I + 4, "R")).Value 'Transfer new berg size to start of day 1
    For J = 1 To 1                                                    'Loop for the one 14 day period
      Worksheets("MeltSim").Range("RandNums").Calculate               'Generate new random deviates
      Worksheets("MeltSim").Range("Temp").Calculate                   'Recalc T

      For HalfDay = 1 To 28 'half days
          Worksheets("MeltSim").Cells(HalfDay + 5, "F").Calculate
          Worksheets("MeltSim").Range(Cells(HalfDay + 5, "J"), Cells(HalfDay + 5, "O")).Calculate
      Next HalfDay
      Worksheets("MeltSim").Cells(29 + 5, "F").Calculate
      Range("F6").Value = Range("F34")

  Next J
  Range(Cells(I + 4, "S"), Cells(I + 4, "S")).Value = Range("F34").Value 'copy new size back
  Worksheets("MeltSim").Range(Cells(HI + 4, "T"), Cells(I + 4, "U")).Calculate
Next I

End Sub
```